Micromachined Devices for Use in Terahertz Applications

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Abstract. Here we present results from key aspects of our interest in using micromachined devices in the THz region. First, our early work on making filters from rods of gold-coated SU8 is described. Pass (up to 97%) and stop bands can be observed which are theoretically underpinned by both FDTD and complex band structure simulations. Second, there is a discussion of how THz radiation passes through two-dimensional periodic arrays of subwavelength apertures. In particular, the geometry of the arrays has been studied with time-domain spectroscopy. A time-of-flight model is presented which can be used to provide insight into the operation of these arrays and has implications for the optimum design of THz plasmonic sensors. Finally, we report the THz 'super' extraordinary transmission properties of an optimised hybrid subwavelength aperture array, surrounded by subwavelength grooves.

Introduction

The idea of controlling the electromagnetic properties of a material through subwavelength engineering has proven to be a prominent topic of research in the past decade. Fuelled by advances in micro and nanofabrication, combined with the exciting desire to develop properties that nature forbids (e.g. invisibility cloaking [1] or negative refractive indices [2]), the field of artificial and metamaterials has emerged. The THz region has suffered from being very much underused compared to other parts of the electromagnetic spectrum. This has been due to a shortage of powerful, coherent sources and also a lack of compact devices with which to control the radiation. THz light provides a non-ionising, and hence safe, probe for studying both spectroscopic and topographical detail. With the use of coherent detection based THz time domain spectroscopy (TDS), it is possible to study the dielectric properties of materials and, importantly, reveal the effect of subwavelength engineering in the time domain.

THz science and technology has advanced considerably in the past decade. Commercial time domain spectroscopy systems are in production and powerful quantum cascade laser (QCL) sources are now operating at below 2 THz [3], albeit still with the assistance of cryogenic cooling. Applications of THz radiation have had impact in such diverse fields as pharmaceutical process control [4], security imaging [5], biology [6], semiconductor characterisation [7] and medicine (e.g. tumour detection) [8].

In spite of recent advances, THz research is still constantly constrained by fundamental scientific and technological limits. Naturally occurring materials do not produce efficient sources and filters at THz frequencies. Furthermore, the sub-millimetre scale wavelength (1 THz is equivalent to a wavelength of 300 μm) poses a significant barrier to high-resolution microscopy. To combat these issues, new materials need to be developed through the exploitation of electromagnetic design and plasmonic effects.

The aim of this subwavelength engineering approach is to create an artificial material which is not readily available in nature. In this paper, we describe two types of artificial materials which have been produced by the Durham THz group in recent years. The first is based on arrays of high aspect ratio metal-coated, polymer rods and the second, periodic arrays of subwavelength apertures in electroformed copper foils. Both devices, however, are shown to act as band pass type filters with the latter also well suited to play a role in surface sensors.

THz measurements

The transmission properties of the artificial materials are measured in a bespoke terahertz time domain spectroscopy system (see Fig. 1). The THz signal is generated by a GaAs photoconductive emitter, pumped by a ~20fs Ti:Sapphire 800nm laser. Parabolic mirrors are used to focus the THz signal onto the sample. The gating and the THz beam are focused onto a 1 mm thick ZnTe electro-optic crystal. This, in conjunction with a balanced detector, is used to detect the THz radiation transmitted through the structure. A delay line on the NIR generation beam allows the electric field of the THz pulse to be scanned in the time domain. A Fast Fourier Transform is then used to obtain a frequency spectrum. This system provides a useable bandwidth of approximately 3 THz. For relative transmission measurements, the sample scan is divided by a free space scan in the frequency domain. This effectively deconvolves any reflected signals associated with the measurement setup.

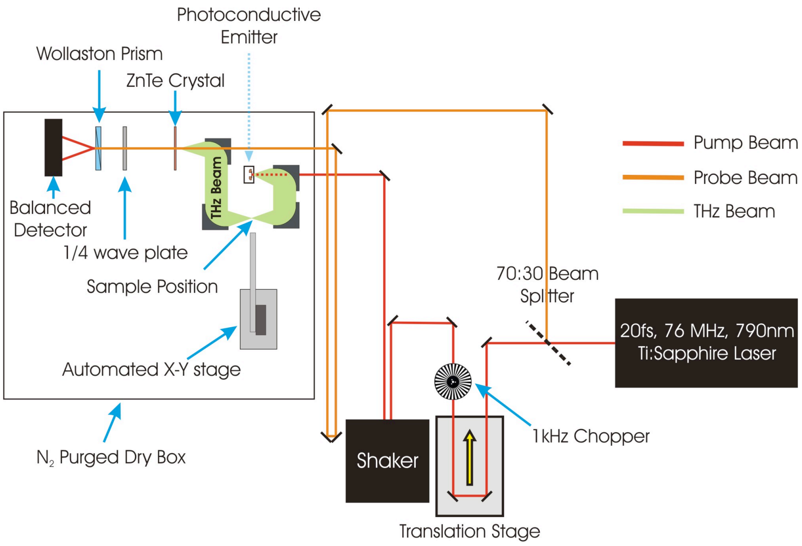

Fig. 1. Schematic of the THz Time Domain Spectroscopy system used to test the micromachined artificial materials.

High aspect ratio metal rod based THz filters

Pendry *et al* [9] reported that a thin wire model could be used to describe the effective plasma frequency of an array of metallic rods. They showed that the effective plasma frequency is a function of the array geometry and is independent of the bulk plasma frequency of the metal. However, to produce an effective plasma frequency in the THz regime, the rods need to be of the order of tens of microns diameter and of sufficient length to fully confine the incident beam [10]. This ‘microbrush’ type of structure is difficult and expensive to fabricate using manual assembly type techniques. A better fabrication approach involves the use of high aspect ratio polymer lithography.

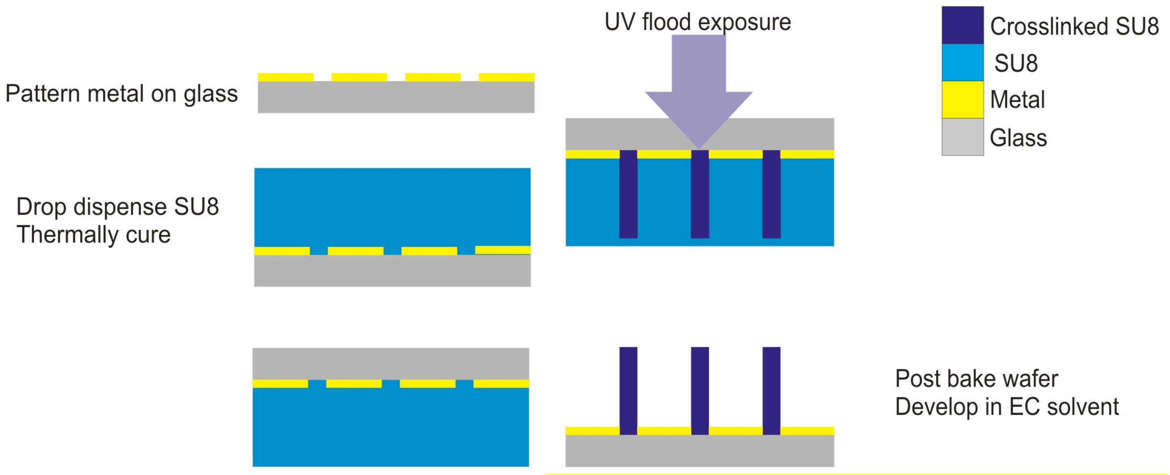

Fig 2. Overview of the fabrication process used to produce high aspect ratio microrods.

Fig. 2 shows an overview of the process flow used to fabricate arrays of microrods. The details of the fabrication process can be found in [10]. The key novelty is the use of backside UV exposure of SU8-50 which can produce structures with diameters as small as 30 μm and heights in excess of 1.5 mm. The SU8 is fairly transparent to THz radiation; therefore the rods have to be sputter coated with gold in order to form the diluted metal structure.

By carefully aligning these rod array based devices in the THz TDS system, described previously, it is possible to measure their transmission characteristics. The samples were placed at the focus of the THz beam and aligned to ensure that the low frequency components were confined in the device (as opposed to passing over the top of the array). The electric field was aligned to be parallel to the rods.

Fig. 3 shows the relative transmission for arrays with various rod diameters but a fixed period of 200 μm. The devices show a clear band structure with peak relative transmission of up to 97% and near zero transmission in the stop bands.

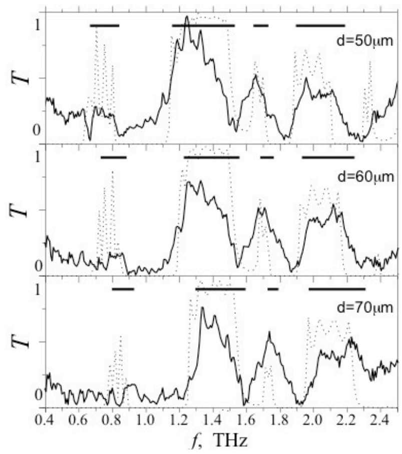

Fig. 3. The relative transmission of arrays of high aspect ratio, gold coated rods. The periodicity is fixed at 200μm in all cases. However, the rod diameter, d, is varied as indicated. The dotted lines are derived from FDTD simulations and the dark horizontal lines show the passbands deduced from complex photonic band theory. After [10].

As the diameter, and hence the fill-factor is increased, the bands move to higher frequencies, with an increasing effective plasma frequency. The results show that a spectral shift associated with a 10 μm change in diameter can readily be detected by the THz TDS system. Fig. 3 also includes the passbands predicted by both complex band theory calculations [10] and Finite Difference Time Domain (FDTD) simulations. Both can be seen to provide an excellent match to the experimental data.

The peak transmission of these devices is sufficiently high to permit the creation of a compound filter [11]. This is when two arrays of rods, each with slightly differing fill factors, are placed back to back. With the photolithographic approach described here, it is straightforward to precisely align the arrays on a shared substrate. Fig. 4 shows the terahertz transmission characteristics and an image of the fabricated compound filter. The complex band structure, shown in Fig. 3, is reduced in the compound filter to a single, well-defined, pass band at a frequency which is determined by the fill factor. Furthermore, by varying the fill factor along the array it is possible to produce a mechanically tunable device [12].

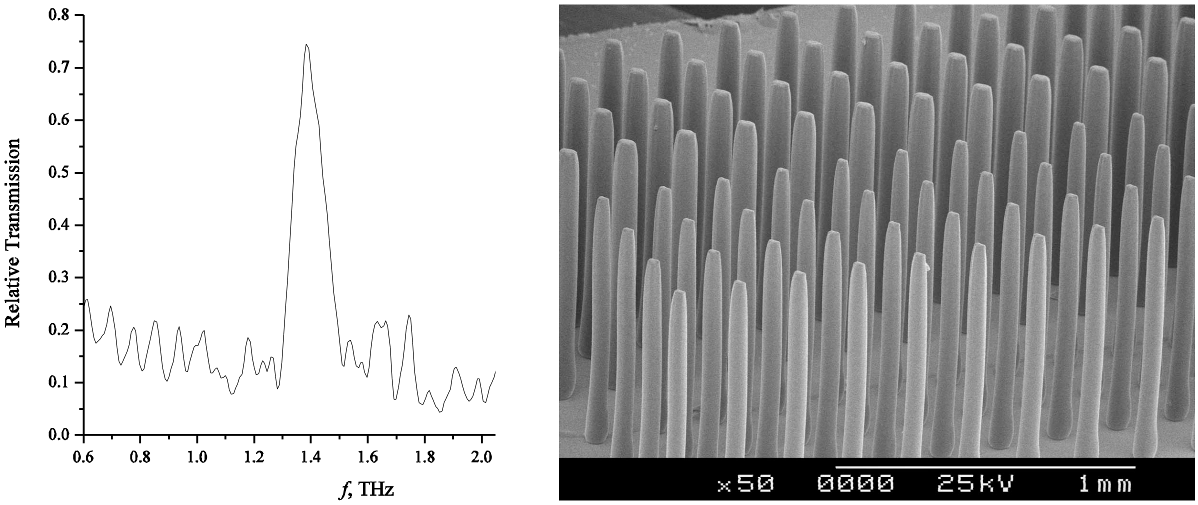

Fig. 4. On the left is the measured transmission characteristic for a compound filter arrangement consisting of 4 lines of metallic rods with a diameter of 50μm, separated by 200μm from another 4 lines of metallic rods each with a diameter of 80μm. In both cases, the rod period was fixed at 200μm. On the right is an image of a fabricated device.

The THz beam in the TDS systems can be focused down to approximately 1 mm diameter in free space. The z thickness achievable with thick SU8 processing is therefore ideal in order to confine the beam. However, this beam confinement requirement and the need to precisely align the device to avoid low frequency components passing over the top of the array still presents a limitation when using this type of structure in real applications. The following section describes an alternative approach based on surface plasmon polariton (SPP) excitation.

Surface plasmon based THz filters

Surface Plasmon Polaritons can be viewed as oscillations of charge propagating along a conductor/dielectric boundary. SPPs are readily excited with visible light and their propagation properties form the basis of the well-established SPR sensing technique in biology. Their optical excitation is relatively straightforward because the plasma frequency of bulk gold and silver is in the UV region, which provides good impedance matching to the incoming light. For SPP effects to work effectively with metals in the THz region, the plasma frequency of the conductor needs to be lowered.

For the successful generation and utilisation of THz frequency SPPs, two features must be present; a launch mechanism which can impart the necessary in-plane momentum to excite SPP modes, and a surface decorated with subwavelength features to increase the confinement of the SPPs.

Subwavelength periodic apertures such as two-dimensional hole arrays serve as extremely efficient plasmonic materials due to their ability to both excite and confine SPPs. The two-dimensional hole array configuration at optical frequencies was described in the first reports of Extraordinary Optical Transmission [13].

Each hole edge in the array acts as a diffraction point at which p-polarised light can couple to SPPs. The two-dimensional lattice provides the in-plane momentum which is required to enable freely propagating light to couple to SPP modes along the metal-dielectric boundary. Although, the precise mechanism for the operation of these arrays is still contested, and no single theory has been found allowing the resonances to fully be explained or predicted, the use of THz TDS presents an interesting method of studying these structures.

A novel fabrication technique using electroformed copper and standard lithographic techniques was devised to create the arrays [14]. To begin, a 30 nm titanium seed was evaporated onto a silicon wafer, on top of which an 80 nm gold layer was evaporated. This metallic layer provided the electrical contact necessary for the electroforming process. A three-layer AZ9260 photoresist process was used to pattern 50 µm high isolated islands of resist, around which copper would be plated to create the arrays. Resist AZ9260 was spin coated at 500 rpm for 10 seconds, followed by 50 seconds at 1500 rpm. After waiting for two minutes, the resist was baked at 95˚C for seven minutes before a one minute cooling step. This spin/bake process was repeated twice, after which an edge bead removal step was undertaken prior to a one hour bake at 95˚C. The resist was then left 24 hours before further processing to ensure all solvents were removed. After exposure through a light field mask for 215 seconds, the resist was developed in 3:1 H_2O:AZ400K developing solution for approximately five minutes until clear. Copper electroforming using a commercial copper plating solution (Via-fill 3000), a sacrificial copper anode and a constant current of 45 mA created a copper foil on the gold surface of the wafer (the cathode). After 45 minutes, a foil of 30 µm thickness was plated. After removing the photoresist in acetone, the copper foil could be peeled directly from the gold seed due to the poor adhesion between the two metals. This produced free-standing, copper foils featuring subwavelength aperture arrays. Free-standing arrays are known to produce sharper resonances due to increased front-to-back coupling of SPPs on either side of the array [15]. Using this fabrication technique, metallic regions as small as 10 µm can be fabricated between apertures, allowing a vast range of aperture aspect ratios to be created.

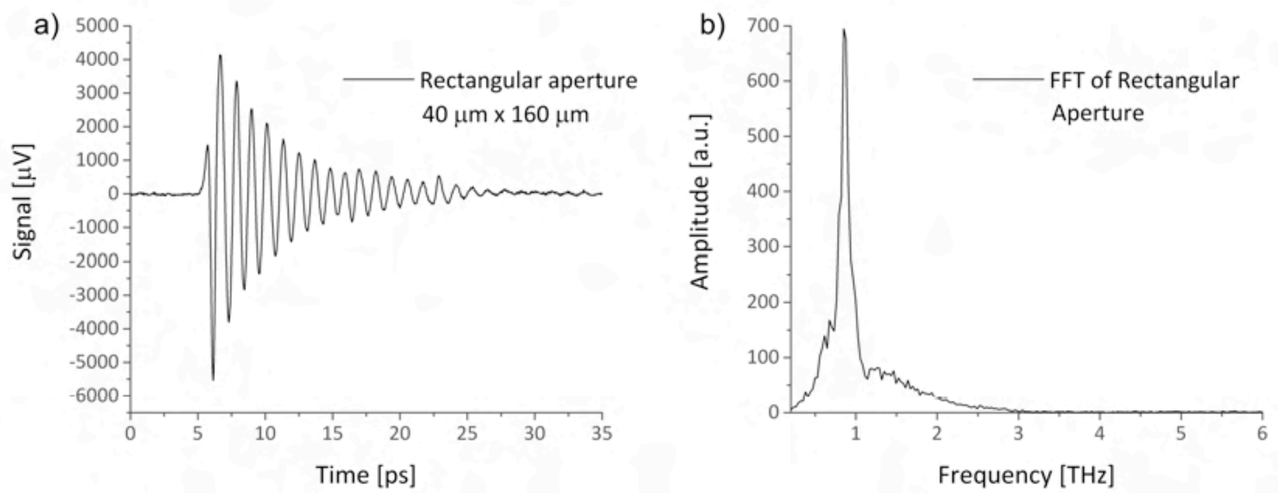

Fig. 5. Time and frequency domain signals for a 300µm period, triangular lattice array of subwavelength 40 µm x 160 µm rectangular apertures. After [14].

For measurement, the foils were placed directly into the focused THz beam path of the TDS system. Unlike the rod type structures, their precise alignment is less critical because the array is surrounded by solid copper and hence any stray beams are effectively blocked.

Fig. 5 shows the transmitted THz signal in both the time and frequency domain for an array of 40 μm x 160 μm rectangular apertures with a 300 μm period, triangular lattice configuration [14]. The transmission peak is at 0.85 THz with a FWHM of 140 GHz. The transmission is eight times greater than would be expected for this exposed area, assuming 100% transmission through the subwavelength apertures – which is not achieved in practice [16].

To further understand the signals shown in Fig. 5, it is possible to adopt a time-of-flight approach when considering SPP excitation and propagation. However, first a knowledge of the coupling and decoupling mechanisms of SPPs is required, as well as an understanding of their propagation direction. Aperture edges act as points at which incident radiation can initiate SPPs, and conversely, SPPs can be decoupled into free space radiation. Once initiated, SPPs propagate radially away from an aperture, with their preferential direction being parallel to the polarisation of the electric field [17]. When the SPPs arrive at an aperture edge, they decouple from the metal-dielectric boundary and continue to propagate as free space radiation. A small proportion of this radiation is transmitted through the aperture allowing for subsequent detection, whilst the remaining majority re-couples as an SPP on the far side of the aperture. The SPP continues along the metal-dielectric boundary, losing a fraction of its intensity from decoupling events at each aperture edge. The periodic nature of the aperture array will produce periodic decoupling events, thus leading to a periodic signal in the time-domain. Furthermore, the amplitude of this signal can be expected to decay in time as the intensity of the SPPs is decreased due to multiple decoupling events along the array. The periodic signal detected in the time domain leads to a transmission peak in the frequency domain. We have used this approach to consider the effect of aspect ratio, periodicity and its role in introducing frequency shifts to the expected responses [14]. A pronounced temporal oscillation is apparent in the Fig. 5 and can be attributed to the successive decoupling of SPPs from the periodic apertures. Fig. 6 shows the transmission properties for a range of aperture aspect ratios. As the aspect ratio is increased, the width of the apertures is decreased and hence the metallic region between the apertures becomes broader. This leads to a longer time between decoupling events and therefore an observed redshift in the peak transmitted frequency.

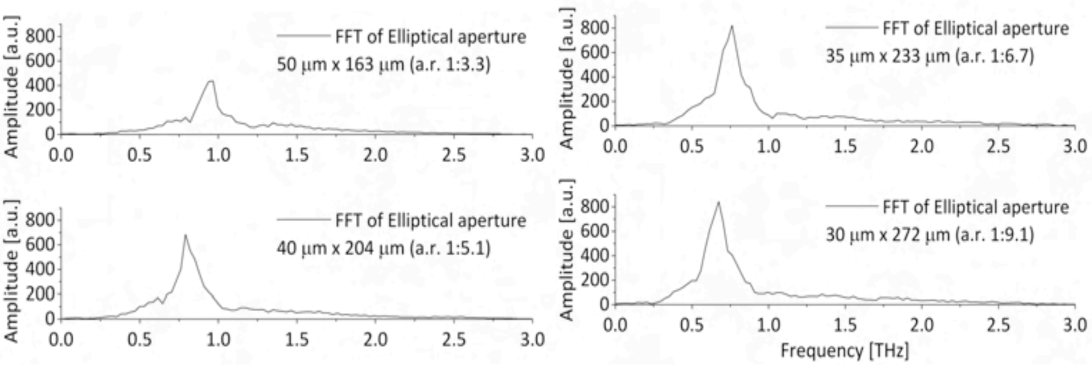

Fig. 6. Transmitted THz through aperture arrays with elliptical apertures of various aspect ratios but a fixed 300μm period, triangular lattice arrangement. After [14].

As an extension to the fabrication process for the hole arrays, an additional mask stage can be introduced to allow corrugated grooves to be included in the structure. These will also act as diffraction points for SPPs and with an appropriate periodicity can also provide surface confinement. Fig. 7 shows a hybrid device with both apertures and grooves and its associated transmission properties (with and without grooves for reference). The apertures are 40 μm x 160 μm with a 300 μm period. By ensuring that the period of the grooves is commensurate with that of the apertures, the SPPs generated at both the grooves and the apertures will combine in phase. Without the surrounding grooves, the transmission is 35 times higher than would be expected based on the exposed area alone. This increases to a 400 times enhancement with the grooves - ‘super’ extraordinary transmission [18].

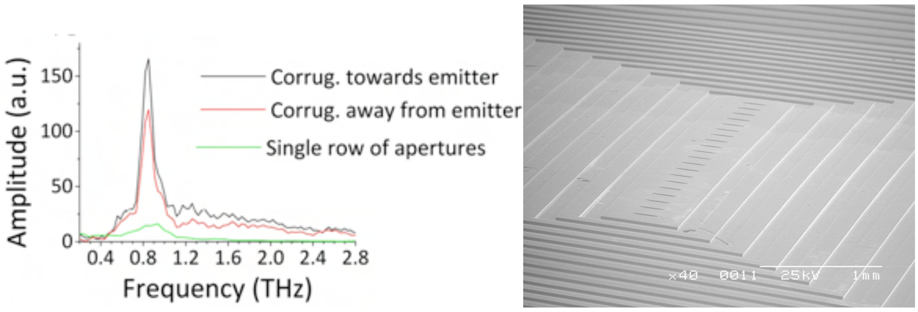

Fig 7. Transmission properties and image of a hybrid aperture/corrugation device. After [18]

In addition to acting as a filter of broadband THz radiation, this structure opens up the possibility of use in THz plasmonic sensing platforms. For example, a powdered sample could be placed in the corrugations, modifying the SPP propagation behaviour in that area. However, the SPPs could continue to decouple from the apertures. Future work could explore the fabrication of microsystems to deliver the sample to a plasmonic sensing surface.

Conclusions

This paper has described two types of terahertz micromachined filters. One was based on the properties of periodic arrays of subwavelength gold-coated polymer rods. The other on extraordinary transmission through free-standing copper foils which contain periodic arrays of subwavelength apertures. The latter device has been considered from a time-of-flight perspective with respect to the propagation of surface plasmon polaritons. Finally, it has been shown that by combining subwavelength apertures and grooves, of a commensurate period, ‘super’ extraordinary transmission occurs. In all cases, the use of micromachining has enabled the straightforward fabrication of these types of devices.

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References

[1] D.R. Smith, J.B. Pendry, and M.C.K. Wiltshire, Metamaterials and Negative Refractive Index, Science, 305 5685 (2004) 788-792.
[2] D. Schurig, J.J. Mock, B.J. Justice, S.A. Cummer, J.B. Pendry, A.F. Starr, D.R. Smith, Metamaterial Electromagnetic Clock at Microwave Frequencies, Science, 314 5801 (2006) 977-980.
[3] S. Kumar, C.W.I. Chan, Q. Hu, J.L. Reno, A 1.8-THz quantum cascade laser operating significantly above the temperature of $\hbar\omega/k_B$, Nat. Phys. 7 (2011) 166-171.
[4] S. Zhong, Y.-C. Shen, L. Ho, R. K. May, J. A. Zeitler, M. Evans, P. F. Taday, M. Pepper, T. Rades, K. C. Gordon, R. Müller, P. Kleinebudde, Non-destructive quantification of pharmaceutical tablet coatings using terahertz pulsed imaging and optical coherence tomography, Opt. and Las. in Eng., 49 3 (2011) 361-365.
[5] J.F. Federici, B. Schulkin, F. Huang, D. Gary, R. Barat, F. Oliveira, D. Zimdars, THz imaging and sensing for security applications – explosives, weapons and drugs, Semcond. Sci. Technol. 20 7 (2005) S266-S280.

[6] D. A. Schmidt, O. Birer, S. Funkner, B.P. Born, R. Gnanasekaran, G.W. Schwaab, D.M. Leitner, M. Havenith, J. Am. Chem. Soc., 131 51 (2009) 18512-18517.
[7] D.M. Mittleman, J. Cunningham, M.C. Nuss, M. Geva, Noncontact semiconductor wafer characterization with the THz Hall effect, *Appl. Phys. Lett.* 71 (1997) 16-18.
[8] R.M. Woodward, B.E. Cole, V.P. Wallace, R.J. Pye, D.D. Arnone, E.H. Linfield, M. Pepper, Terahertz pulse imaging in reflection geometry of human skin cancer and skin tissue, Phys. Med. Biol. 47 (2002) 3853-3863.
[9] J.B. Pendry, A.J. Holden, W.J. Steward, I.I. Youngs, Extremely low frequency plasmons in metallic mesostructures, Phys. Rev. Lett. 76 25 (1996) 4773-4776.
[10] A.J. Gallant, M.A. Kaliteevski, S. Brand, D. Wood, M. Petty, R.A. Abram, J.M. Chamberlain, Terahertz frequency bandpass filters, J. Appl. Phys. 102 2 (2007) 023102.
[11] A.J. Gallant, M.A. Kaliteevski, D. Wood, M.C. Petty, R.A. Abram, G. P. Swift, D.A. Zeze, J.M. Chamberlain, Passband filters for terahertz radiation based on dual metallic photonic structures, Applied Physics Letters, 91 16 (2007) 161115.
[12] A.J. Gallant, G.P. Swift, D. Dai, M.A. Kaliteevski, D.A. Zeze, D. Wood, M.C. Petty, S. Brand, R.A. Abram, J.M. Chamberlain, Micromachining for Terahertz Applications, MRS Proceedings, 1016 (2007) 1016-CC05-07.
[13] T.W. Ebbesen, H.J. Lezec, H.F. Ghaemi, T. Thio, P.A. Wolff, Extraordinary transmission through sub-wavelength hole arrays, Nature, 391 (1998) 667-669.
[14] A.J. Baragwanath, M.C. Rosamond, A.J. Gallant, J.M. Chamberlain, Time-of-Flight Model for the Extraordinary Transmission Through Periodic Arrays of Subwavelength Apertures at THz frequencies, Plasmonics, 6 4 (2011) 625-636.
[15] A. Krishnan, T. Thio, T. J. Kim, H. J. Lezec, T. W. Ebbesen, P. A.Wolff, J. Pendry, L. Martin-Moreno, F. J. Garcia-Vidal, Evanescently coupled resonance in surface plasmon enhanced transmission, Opt. Commun., 200 (2001) 1 – 7.
[16] H.A. Bethe, Theory of diffraction by small holes, Phys. Rev. 66 (1944) 163-182
[17] R. Gordon, A. G. Brolo, A. McKinnon, A. Rajpra, B. Leathem, K. L. Kavanagh, Strong polarization in the optical transmission through elliptical nanohole arrays, Phys. Rev. Lett., 92 3 (2004) 037401
[18] A.J. Baragwanath, M.C. Rosamond, A.J. Gallant, J.M. Chamberlain, A hybrid aperture-corrugation plasmonic device demonstrating super extraordinary transmission at terahertz frequencies, Proceedings of Infrared, Millimeter and Terahertz Waves, Houston, TX, October (2011) 1-2.